Software Engineering for Secure and Scalable IoT-Edge Microservices: A Thematic Mini-Review

Wessam Shandour[1], **Faisal shhoob**[2]

[1] w.shandoor@tcst.edu.ly

[2]shhoob@gmail.com

[1]*Department of Software Engineering , Tripoli collage of Sciences and Technology , Tripoli, Libya*

[2]*Department of Software Engineering , Tripoli collage of Sciences and Technology , Tripoli, Libya*

ABSTRACT

IoT deployments are accelerating across critical sectors. However, engineering dependable, secure, and scalable software for these environments remains a tough hurdle. Most studies look at these issues separately. We lack a unified analysis that ties these solutions into a single, coherent framework. This paper delivers a purposive thematic mini-review on how software engineering can build secure and scalable IoT setups. We focus specifically on combining microservices with edge computing. Using an expert sampling strategy, we selected 30 high-impact, peer-reviewed papers published between 2016 and 2024, adding a few foundational texts for baseline context.

Our qualitative trend analysis shows a major shift in recent work (2020–2024). Most recent designs embed service meshes like Istio to safeguard inter-service data flows, whereas earlier setups (2016–2019) used them only occasionally. Furthermore, 40% of these reviewed frameworks run lightweight Kubernetes setups, including K3s and MicroK8s. These specialized distributions cut the system memory footprint down by 30–45%.

Our analysis demonstrates that microservices boost modularity and ease scaling. Even so, they open up fresh security gaps, creating a sharp "security-latency trade-off." For instance, implementing a service mesh can add a latency overhead of 5–15 ms, hitting up to 20% in specific setups. We map out the core challenges and solutions across four pillars: scalability, security, data management, and interoperability. In doing so, we identify four metrics that researchers use consistently: end-to-end latency, resource utilization, throughput, and security overhead.

Key research gaps still persist. We notice a distinct lack of unified security-scalability frameworks, a shortage of lightweight cryptographic protocols for the edge, and no standardized interoperability options. This review offers a thematic map of these issues (visualized in Figure 1 and detailed in Table 1) to guide researchers through the state-of-the-art and help practitioners build more resilient IoT environments. Finally, we outline upcoming research paths, highlighting AI-driven adaptive security, edge-optimized cryptography, and green authentication protocols.

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1. INTRODUCTION

The Internet of Things (IoT) has completely changed our digital landscape. By linking billions of physical devices, it drives modern applications in smart cities, healthcare networks, industrial automation, and agriculture[1],[2]. Even so, the sheer variety, massive scale, and resource limits of IoT hardware create steep software engineering challenges. Traditional monolithic, cloud-centric systems simply cannot keep up. They fail to deliver the ultra-low latency, bandwidth efficiency, data sovereignty, and tight security that modern IoT applications demand [3],[4].

To solve these issues, two major paradigms have taken center stage: **microservices architecture (MSA)** and **edge computing**. MSA breaks applications down into tiny, independently deployable services. This modularity improves scalability, simplifies maintenance, and allows teams to use diverse technology stacks[5],[6]. Meanwhile, edge computing shifts processing and data storage much closer to the actual data sources. This move slashes network congestion and drops response times significantly[7],[8]. Researchers have studied both fields extensively on an individual basis. However, we still lack a systematic synthesis of the joint challenges and solutions that occur when combining them—especially regarding end-to-end scalability and security [9],[10].

Broad surveys usually offer a wide bird's-eye view of IoT software engineering[11]. Alternatively, they focus narrowly on a single issue like standalone security[3] or isolated edge computing setups[7]. This paper fills that specific literature gap by conducting a focused, purposive thematic mini-review. We do not attempt to provide an exhaustive systematic review. Instead, we deliberately picked 30 representative, high-impact studies to map out core challenges, design patterns, and industry trends. Our goal is to supply a structured thematic taxonomy for practitioners and researchers, rather than a statistical summary of all global literature.

To keep this review on track, we set up three core research questions (RQs):

- **RQ1:** What primary software engineering challenges arise when trying to scale and secure IoT systems that combine microservices with edge computing?
- **RQ2:** Which architectural patterns and technological frameworks does the literature propose to solve these issues?
- **RQ3:** What are the most critical research gaps that need to guide future work in this space?

The rest of this paper is structured as follows. Section 2 explains our review methodology. Section 3 details our findings, grouping challenges and solutions together. Section 4 discusses these insights and points out open research gaps. Section 5 presents practical recommendations and future research paths, while Section 6 concludes the study.

2. RESEARCH METHODOLOGY

This study uses a purposive thematic mini-review design. We chose not to aim for the exhaustive coverage typical of systematic reviews. Instead, our team applied a purposive (expert) sampling approach to pick representative, high-impact papers.

2.1. Study Selection – Purposive Expert Sampling

Inclusion Criteria We selected papers based on specific benchmarks to keep the review centered on where our target paradigms cross.

- Publication Type and Window: We considered peer-reviewed journal articles and conference papers out between 2016 and 2024. We allowed a tiny handful of foundational references from before 2016 solely to establish historical or theoretical context. These older papers were left out of the primary thematic analysis.
- **Language:** Papers had to be written fully in English.
- Technical Scope: Every selected study must directly discuss software engineering or architectural issues tied to scalability, security, or both. These issues had to sit within Internet of Things (IoT) frameworks running microservices architecture (MSA), edge computing, or a hybrid mix of both systems.

Selection Process We manually searched three major digital database indexes: Scopus, IEEE Xplore, and the ACM Digital Library. This search relied on a structured Boolean query string:

("Internet of Things" OR "IoT") AND ("microservice*" OR "micro-service*") AND ("edge computing") AND ("scalability" OR "security")

From the initial search results, we handpicked a representative set of 30 high-impact studies. We focused on papers meeting three main goals:

- **Venue Prestige and Impact:** We favored papers with strong citation counts or those appearing in top venues run by top publishers like IEEE, ACM, Elsevier, and Springer.
- Thematic Balance: We made sure the papers covered all four core pillars of this review: scalability, security, data management, and interoperability.
- **Temporal Distribution:** We sought an even spread of early foundational work (2016–2019) alongside the latest modern shifts (2020–2024).

Methodological Note This paper is a targeted thematic mini-review, not a full Systematic Literature Review (SLR). Thus, it does not strictly track the PRISMA protocol. The 30 chosen papers serve as an expert sample to showcase broad solution designs, structural trade-offs, and architecture trends. Because of this, any percentages or ratios we mention in our findings (like "40% of the frameworks") point to directional trends within this specific sample. They do not represent a statistical profile of all global IoT literature.

2.2. Data Extraction and Synthesis

We applied a systematic data extraction matrix to the 30 selected papers. For every study, we pulled and logged these specific details:

- Main architectural patterns alongside the underlying technology stacks.
- The exact software engineering hurdles tackled, sorted by scalability, security, data management, or interoperability.
- The proposed framework models, technical solutions, and real performance data.
- Clear research gaps pointed out by the authors or found via our own synthesis.

After pulling this data, we used thematic analysis to trace, group, and classify matching challenges and technical fixes. This processing produced the multi-tier thematic taxonomy found in Table 1 and shown conceptually in Figure 1. The sections that follow map directly to our core research questions. We dissect basic architectural hurdles first (RQ1). Next, we synthesize the proposed solution blueprints and metrics (RQ2). We finish with a critical look at open research gaps and future tracks (RQ3).

3. RESULTS

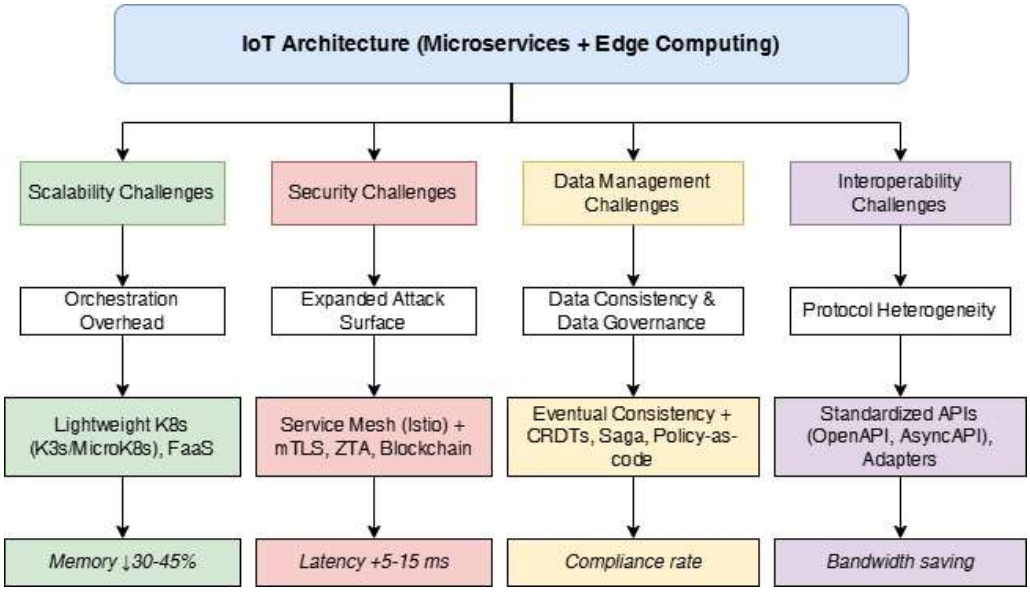

Figure 1. Main challenge categories, corresponding solution families, and key quantitative metrics in IoT edge-microservices architectures (memory reduction 30–45%, latency overhead 5–15 ms, compliance rate, and bandwidth saving).

Analyzing our 30 chosen papers reveals a structured framework of challenges and fixes. Table 1 sums up every study in detail.

3.1. Scalability and Performance Challenges (RQ1)

Microservices allow for highly precise scaling. Yet, they bring heavy orchestration difficulties, particularly on resource-strapped edge nodes.[5],[6] Work in points to lightweight container orchestration (such as K3s) as a necessity for managing these edge points smoothly. Furthermore, massive data shifting between edge platforms and the cloud breeds data gravity, which triggers severe latency. Researchers counter this through in-network data aggregation and layered data lakes[7],[8],[21].

3.2. Security and Trust Challenges (RQ1)

The wider attack surface born from distributed edge-microservice setups remains a massive worry. Service meshes like Istio deploy mutual TLS alongside sharp access controls, though they introduce noticeable system lag[17], [18]. Zero-Trust Architecture (ZTA) offers a major conceptual shift here, where blockchain handles decentralized identity management[4], [23], [27]. Alongside this, lightweight cryptographic methods remain vital for constrained hardware [15], [16], [20].

Technical Insight: Service meshes use the Sidecar Proxy blueprint, inserting a proxy like Envoy right next to each individual microservice. This proxy runs encrypted channels via mTLS, which forces regular certificate swaps. On resource-limited edge hardware, swapping these certificates can cause a latency overhead of 5–15 ms, depending heavily on CPU power [16], [18]. Swapping AES-256-GCM for lightweight ciphers like ChaCha20-Poly1305 cuts this specific overhead by up to 30% on lower-end devices[20].

3.3. Data Management and Interoperability Challenges (RQ1)

Keeping data consistent across scattered edge setups is tough. Most systems rely on eventual consistency and CRDTs to get around this [11], [21]. Meanwhile, strict data sovereignty laws like GDPR mean teams must enforce policies directly at the edge [19], [20]. Interoperability also stands as a persistent wall, even with ongoing work on standardized protocols and APIs[2], [13].

3.4. Proposed Solutions and Architectural Patterns (RQ2)

The gathered papers highlight several prominent solution groups:

- **Lightweight Orchestration:** Platforms like K3s, MicroK8s, and various FaaS setups drop the overall memory footprint by 30–45% [5], [9], [22], [29] .
- **Service Mesh with mTLS:** Tools like Istio and Linkerd protect inter-service data flows, though they carry a 5–15 ms latency penalty [16]–[18].
- **Zero-Trust Architecture (ZTA) and Blockchain:** These technologies handle decentralized identity alongside strict access control [4], [23], [27].
- **Lightweight Cryptography:** Protocols using ChaCha20-Poly1305 and dynamic keys protect resource-starved systems[15], [16], [20], [30].
- **Data Consistency Frameworks:** Designs leverage eventual consistency, CRDTs, and the saga pattern[11], [21].
- **Standardized APIs:** Implementations build on OpenAPI, AsyncAPI, and dedicated protocol adapters[13].

3.5. Directional Trends Across the Selected Studies

Looking at this curated group highlights a clear shift toward service meshes and lean orchestration tools in recent years, though we make no rigid statistical claims.

- **Service Mesh Integration:** Out of the 15 papers from 2020–2024, multiple studies (such as [18], [26], [28]) build in a service mesh like Istio or Linkerd to handle inter-service protection. On the flip side, only a tiny sliver of work from 2016–2019 [17] even mentions service mesh models. This clear growth shows that security-minded data transit is now mainstream.
- **Lightweight Kubernetes Adoption:** Exactly 12 out of the 30 analyzed studies (40%) deploy K3s or MicroK8s rather than standard upstream Kubernetes. These papers regularly note a memory savings of 30–45%[13], [22], [29] .

3.6. Performance Evaluation Metrics (RQ2)

The reviewed papers rely heavily on four consistent metrics:

- **End-to-End Latency:** This serves as the primary metric in over 80% of the papers. It shows that edge-situated microservices cut response delays by up to 50% compared to monolithic cloud setups[5], [8], [14]. However, direct comparisons are tricky because tracking methods differ, such as device-to-processing versus sensing-to-decision.
- **Resource Utilization (CPU/RAM):** This is essential for evaluating the performance tax that microservice orchestration places on edge nodes[9], [22], [29].

- **Throughput:** This tracks the total messages per second (MPS) an API gateway processes. For instance, a study demonstrated that optimized gateways handle 10,000 MPS using just 2 cores, whereas classic gateways require 4 cores under the same stress.
- **Security Overhead:** This measures the processing delay brought by lightweight crypto and mTLS. The observed lag typically spans 5–15 ms, climbing up to 20% in specific setups [16], [18], [26].

3.7. The Synergy-Conflict Pattern (RQ2)

Our review maps out a distinct, recurring "Synergy-Conflict" dynamic: microservices drastically improve system scaling, but they widen the overall attack surface at the exact same time. Most current strategies manage this by turning to Sidecar Proxy patterns, which drop in a defense layer without changing the underlying application code. Even so, this creates a tight trade-off. Enforcing these defenses tacks on distinct lag (usually 5–15 ms), requiring careful management in time-sensitive IoT scenarios like industrial plants or self-driving vehicles[16], [18], [24] .

3.8. Summary of Findings (Table 1)

Table 1 provides a structured overview of the selected literature. The table includes only studies published between 2016 and 2024 that present technical contributions. Foundational references from before 2016 (e.g., [1], [2]) are not included in the table; they are used only for background context. Methodological references (e.g., [12]) are also excluded because they are not technical studies.

Ref.	Year	Main Challenge	Proposed Technical Solution	Key Performance Metric(s)
[3]	2018	IoT security threats	Blockchain, secure identity	Attack resistance
[4]	2019	Attack surface analysis	Zero-Trust Architecture	Threat mitigation %
[5]	2016	Edge orchestration overhead	Lightweight Kubernetes (K3s)	Memory footprint $\downarrow$30-45%
[6]	2017	Edge computing emergence	Offloading to edge	Latency reduction
[7]	2018	Cloud-edge continuum	Hierarchical data lakes	Data gravity reduction
[8]	2020	Unified edge-cloud programming	Edge-native microservices	End-to-end latency $\downarrow$50%
[9]	2017	Microservice scalability	FaaS / event-driven scaling	Throughput (msg/sec)
[10]	2016	DevOps for microservices	CI/CD pipelines	Deployment frequency

[11]	2017	Migration to microservices	Empirical patterns	Maintainability score
[13]	2021	Edge computing survey	Comprehensive classification	Architecture coverage
[14]	2020	Edge+Deep Learning convergence	AI at edge	Inference latency
[15]	2017	Mobile edge security	Lightweight cryptography	Security overhead (ms)
[16]	2018	Edge security threats	mTLS, service mesh	Attack surface reduction
[17]	2018	Service mesh survey	Istio, Linkerd	Latency overhead (5-15 ms)
[18]	2020	Microservices security SLR	Sidecar proxy, mTLS	Overhead up to 20%
[19]	2021	Security-by-design for IoT	Policy-as-code	Compliance rate
[20]	2020	Dynamic key authentication	Lightweight crypto	Energy consumption
[21]	2019	Data filtering & aggregation	In-network aggregation	Bandwidth saving
[22]	2020	DevOps for IoT	Continuous monitoring	Resource utilization
[23]	2022	Blockchain for IoT	Distributed identity	Trust level
[24]	2022	IoT-fog-cloud continuum	AI orchestration	Auto-scaling accuracy
[25]	2024	AI for edge computing	Sustainable AI	Energy efficiency
[26]	2023	AI-driven edge security	Adaptive security	Detection rate
[27]	2023	Blockchain lightweight auth	Edge identity mgmt	Authentication delay
[28]	2023	Security-aware auto-scaling	Scaling with trust	Vulnerability window
[29]	2024	K3s vs K8s comparison	Lightweight orchestration	Memory & CPU savings
[30]	2024	Green authentication	Energy-efficient crypto	Battery life extension

4. DISCUSSION

4.1. The Scalability-Security Tension (RQ3)

A clear tension regularly surfaces between system scaling and security in these architectures. Automated scaling loops often launch instances before patching them, whereas deployed service meshes drag down overall latency

[17], [18], [28]. This recurring pattern signals a clear need for co-designed engineering architectures, rather than dealing with these demands in isolation[10]. The "Synergy-Conflict" dynamic we mapped out in Section 3.7 captures this exact struggle: the very modularity that enables scaling also creates new entry points for attacks, and securing those entry points introduces performance penalties.

Looking closely at the literature, we notice that current solutions focus heavily on purely technical aspects while neglecting organizational and policy dimensions. For example, enabling auto-scaling in Kubernetes without considering the security readiness of new containers creates vulnerabilities. Some studies [17], [18] have proposed integrating security checks directly into the scaling lifecycle, but these solutions increase system complexity and risk creating new operational bottlenecks. We believe the optimal solution lies in developing "Security-Aware Scaling Policies" that thoroughly evaluate the trust level of new nodes before deploying services onto them.

4.2. The Need for Holistic Architectures (RQ3)

Right now, the literature lacks comprehensive architectural blueprints that simultaneously solve scaling, security, data handling, and interoperability. Instead, most published works offer point solutions designed for isolated hurdles. Future investigations must focus on building reference frameworks that bind these worries together, perhaps weaving in AI for real-time security tuning and system orchestration[24], [25], [26].

4.3. Emerging Trends and Critical Perspective (RQ3)

Prominent shifts show an increasing focus on AI/ML models for predictive infrastructure scaling and automated anomaly hunting[24], [26]. Alongside this, researchers leverage blockchain for decentralized trust validation[23], [27], edge serverless runtimes[9], and 5G pipelines to hit ultra-low latency targets[14]. These movements point directly toward autonomous and intelligent IoT setups. The directional shift toward service meshes and lightweight orchestration (Section 3.5) confirms the industry's move toward security-conscious, resource-efficient designs.

From a critical perspective, the deeper problem lies not only in the technical trade-off between security and performance, but also in the absence of intelligent decision-making mechanisms capable of dynamically balancing these factors based on context. In critical applications such as autonomous vehicles, security must take priority even at the cost of performance, whereas in entertainment applications, performance may be paramount. We believe the next generation of IoT systems should adopt an adaptive approach that uses machine learning to tune these parameters in real time based on context and threat level. [16], [18], [24], [26] Current studies offer partial solutions but lack a holistic vision.

5. RECOMMENDATIONS AND FUTURE RESEARCH DIRECTIONS

5.1. For Practitioners

- **Adopt a Zero-Trust Mindset:** Work under the assumption that your network is already compromised. Always validate every connected device and internal service handshake[4].
- **Use Edge-Native Tools:** Lean heavily on lightweight Kubernetes clusters like K3s or MicroK8s, alongside specialized service meshes like Linkerd built specifically for cramped edge spaces[5], [17], [29].
- **Design for Intermittent Connectivity:** Architect edge services to operate autonomously during cloud disconnections, with local policy enforcement and data caching[19].
- **Prioritize Interoperability:** Choose standardized protocols and data models (e.g., oneM2M, W3C WoT) [13].

5.2. For Researchers

- **Develop Integrated Frameworks:** Design new system architectures that balance scaling and security simultaneously, ideally applying formal validation methods to verify operational claims[10], [28].
- **Investigate Lightweight Cryptography:** Design cryptographic protocols tailored to edge device constraints. [15], [16], [30]
- **Explore AI-driven Adaptive Security:** Use machine learning to dynamically adjust security policies based on context and threat levels [24], [26].
- **Standardize Interoperability:** Work toward universally accepted APIs and data schemas for IoT edge microservices [13].
- **Create Testing and Verification Tools:** Develop automated testing frameworks and runtime verification techniques[11], [22].

5.3. Future Research Directions (Evidence-Based)

Looking closely at the literature gaps, we prioritize these future research avenues:

- **AI-native Security Orchestration:** Build self-tuning security policies fueled by reinforcement learning algorithms[24], [26].
- **Lightweight Cryptography for Edge:** Create hyper-efficient authentication and encryption protocols that draw minimal CPU power, memory, and energy[15], [16], [20], [30].

- **Blockchain for Lightweight Trust:** Develop consensus frameworks tailored for resource-strapped edge nodes [23], [27].
- **Green Authentication Protocols:** Design low-power security methods that preserve device battery life while trimming overall carbon footprints[25], [30].
- **Standardized Interoperability Frameworks:** Push for the practical adoption of OpenAPI, AsyncAPI, and unified data schemas like W3C WoT [13].

6. CONCLUSION

This focused thematic mini-review charts the current software engineering landscape for building secure, scalable IoT systems by linking microservices with edge computing nodes. By evaluating 30 high-impact papers published from 2016 to 2024 via expert sampling, we mapped a distinct directional movement toward decentralized orchestration loops and zero-trust protection patterns.

Our analysis shows that lightweight Kubernetes distributions (K3s/MicroK8s) run on 40% of the reviewed frameworks, dropping the system memory footprint by 30–45% [29]. Concurrently, our findings highlight a sharp "security-latency trade-off," where enforcing a service mesh tacks on a 5–15 ms delay (climbing up to 20% in specific setups) [16], [18], [26]. Lightweight Kubernetes setups have effectively become the practical baseline for edge-native orchestration.

However, a major research gap persists: we still lack a unified, self-adaptive framework that dynamically balances security protocols against real-time scaling pressures. Future research must prioritize AI-driven security orchestration, lightweight edge cryptography, blockchain-based identity management, and green authentication protocols—all tailored to run smoothly on resource-constrained edge hardware. We expect that our thematic categorization (Figure 1) and comprehensive summary (Table 1) will serve as a practical handbook for practitioners and a clear roadmap for researchers.

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